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Disclaimer

Combined plate motion and density driven flow in the asthenosphere beneath Saudi Arabia: evidence from shear-wave splitting and seismic anisotropy

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ABSTRACT

A comprehensive study of mantle anisotropy along the Red Sea and across Saudi Arabia was performed by analyzing shear-wave splitting recorded by stations from three different seismic networks: the largest, most widely distributed array of stations examined across Saudi Arabia to date. Stations near the Gulf of Aqaba display fast orientations that are aligned parallel to the Dead Sea Transform Fault, most likely related to the strike-slip motion between Africa and Arabia. However, most of our observations across Saudi Arabia are statistically the same, showing a consistent pattern of north-south oriented fast directions with delay times averaging about 1.4 s. Fossilized anisotropy related to the Proterozoic assembly of the Arabian Shield may contribute to the pattern but is not sufficient to fully explain the observations. We feel that the uniform anisotropic signature across Saudi Arabia is best explained by a combination of plate and density driven flow in the asthenosphere. By combining the northeast oriented flow associated with absolute plate motion with the northwest oriented flow associated with the channelized Afar plume along the Red Sea, we obtain a north-south oriented resultant that matches our splitting observations and supports models of active rifting processes. This explains why the north-south orientation of the fast polarization direction is so pervasive across the vast Arabian Plate.

INTRODUCTION

When deformed by dislocation creep, olivine in the upper mantle develops lattice preferred orientations (LPO), where the fast a-axes become parallel to the induced shear, leading to velocity variations with propagation direction (Christensen, 1984; Mainprice and Silver, 1993). Shear waves encountering such anisotropic regions will split into two orthogonal components, one traveling faster than the other. The anisotropy can be characterized by the polarization direction of the fast wave (φ) and the delay time between the fast and slow waves (δt), and these measurements can be used to provide constraints on the mechanisms causing deformation in the upper mantle (Silver and Chan, 1991; Vinnik et al., 1992). In rift environments, one may expect φ oriented perpendicular to the rift since LPO should develop parallel to extension. However, it has been shown in a number of rift environments, such as the Baikal Rift zone, the Rio Grande Rift, and the East African Rift, that the observed φ is actually closer to rift-parallel (Gao et al., 1997; Gashawbeza et al., 2004; Walker et al., 2004). This may indicate more complex rifting mechanisms or other deformation processes that overprint extension signatures. For the East African Rift, it has been suggested that anisotropy observations are not associated with present-day plate motion and asthenospheric shear, but rather reflect previous tectonic episodes whose anisotropic signature has been “frozen” into the lithosphere (Gashawbeza et al, 2004; Walker et al., 2004).

Saudi Arabia and the Red Sea Rift zone offer an excellent environment in which to study the seismic anisotropy associated with rifting and extension. Several different types of models have been proposed to explain how continental rifting in the Red Sea developed. The passive rifting model assumes simple shear conditions where extensional stresses are accommodated on large-scale detachment planes extending through the entire lithosphere below the rift. Flow beneath the rift is parallel to the direction of extension as the underlying asthenosphere is passively upwelled, which would predict a rift-perpendicular φ (Wernicke, 1985; Voggenreiter et al., 1988). The active rifting model involves thinning of the lithosphere by flow in the underlying asthenosphere and requires the presence of hot, ascending material (Camp and Roobol, 1992; Ebinger and Sleep, 1998; Daradich, 2003). In this case, local convection may lead to more complicated flow patterns and therefore more complex anisotropy at depth. Several studies have suggested that these two end-member models may not be mutually exclusive; rifting in the Red Sea may have been initiated by far-field collision and passive processes, followed by more recent active processes associated with a mantle plume (Camp and Roobol, 1992; Ebinger and Sleep, 1998; Daradich et al., 2003).

Several previous studies have examined the anisotropic characteristics in the vicinity of the Red Sea Rift and show a fairly consistent pattern. Using 8 PASSCAL stations across the Arabian Shield (Figure 1), Wolfe et al. (1999) performed shear-wave splitting analysis and found δt of 1.0-1.5 s and φ oriented approximately north-south. Using receiver functions, Levin and Park (2000) found evidence for a more complex anisotropic structure beneath PASSCAL station RAYN (Figure 1), consisting of two dipping layers at depth, but again with a resultant φ oriented north-south. Further north, Schmid et al. (2004) and Levin et al. (2006) examined splitting at several stations near the Gulf of Aqaba and the Dead Sea Transform Fault, where they found average δt of about 1.3 s and φ slightly east of north, with some evidence for a more complex, two-layer anisotropic model. However, each of these studies was somewhat limited in their station distribution and data availability.

In this study, we present a more comprehensive analysis of the anisotropic signature along the Red Sea and across Saudi Arabia by analyzing shear-wave splitting recorded by stations from three different seismic networks. This is the largest, most widely distributed array of stations examined across Saudi Arabia to date. We demonstrate that the north-south orientation of the fast polarization direction is not just valid at isolated sites on the Arabian Shield, but extends throughout the whole of Arabia. We feel that the observations may be influenced by fossilized anisotropy dating back to the Proterozoic, but are dominated by a combination of both plate and density driven flow in the asthenosphere.

SHEAR-WAVE SPLITTING ANALYSIS AND RESULTS

Teleseismic data recorded on broadband instruments from three different seismic arrays were used. The largest array, the Saudi Arabian National Digital Seismic Network (SANDSN), is operated by the King Abdulaziz City for Science and Technology (KACST) and includes 25 broadband stations distributed along the eastern edge of the Red Sea and across Saudi Arabia (Figure 1). Under a unique agreement with KACST, data from events occurring since 2000 have been provided for study (Al-Amri and Al-Amri, 1999). To supplement the SANDSN coverage, we also analyzed data recorded by the 8 stations of the PASSCAL Saudi Arabian Broadband Array, which operated from November 1995 to March 1997 (Vernon and Berger, 1998), as well as data recorded between 1998 and 2001 from 2 stations deployed in Jordan, which are jointly operated by the Jordan Seismological Observatory, Lawrence Livermore National Laboratory, and the U.S. Geological Survey (Rodgers et al., 2003; Figure 1).

We primarily analyzed SKS phases recorded at these stations, but S phases and a few SKKS observations were also included to improve the incidence angle and back-azimuth coverage. The phases of interest were band-pass filtered between 0.05 and 1 Hz to remove long-period signal and high frequency noise. For events displaying clear signal, measurements of the splitting parameters, including φ, δt, and their associated errors, were made using the approach of Silver and Chan (1991). In total, we selected 104 records of SKS phases, 7 records of SKKS phases, and 24 records of S phases, using a total of 135 events. See the electronic auxiliary material for details on which events were used, examples of the waveform analysis, and the resulting measurements.

The splitting parameters from different events at each station were averaged to find an overall resultant and these are shown in Figure 2. In general, the stations display a north-south oriented φ with an average δt of 1.4 s, similar to the findings of previous studies throughout the area (Wolfe et al., 1999; Levin and Park, 2000; Schmid et al., 2004; Levin et al., 2006). Statistical analyses, including the student t-test and weighted averages (Taylor, 1982), were used to examine the variation in splitting observations at individual stations more closely and to compare the observations from different stations to one another. None of the stations showed significant back-azimuth variation, implying that multiple layers of anisotropy or dipping anisotropic symmetry axes are not required, and the observations at most stations were statistically indistinguishable. The stations near the Gulf of Aqaba (Figure 2 inset) are a noteable exception. While statistically similar to one another, this group of stations displays a statistically different (at a 95% confidence level) average φ that is rotated further east than the other stations examined.

DISCUSSION

Gulf of Aqaba Stations

The statistically different measurements in the Gulf of Aqaba region are similar to observations made at nearby stations by Schmid et al. (2004) and Levin et al. (2006). At the two stations they examined, Schmid et al. (2004) found an average φ of 3˚-8˚ east of north and a δt of about 1.3 s. They argue that the fast axis orientation is parallel to the Dead Sea Transform (DST) system and believe that this orientation is due to the strike-slip motion between Arabia and Africa. Levin et al. (2006) examined both one- and two-layer models fitting the splitting parameters in this area, and they argue that the data can be best fit by a two-layer model, where neither layer has a φ parallel to the DST. Their interpretation is that the two-layer model reflects deformation in the asthenosphere caused by absolute plate motion overlain by fossilized anisotropy. Our observations at stations near the DST can be fit by a two-layer model similar to the one proposed by Levin et al. (2006); however, this fit is not statistically better than our one-layer model given the larger degrees of freedom. Therefore, we feel that the splitting observations at the Gulf of Aqaba stations can be best explained by a one-layer model whose φ is oriented parallel to the DST. This concurs with the findings of Schmid et al. (2004) and is similar to observations made along other transform boundaries where fault parallel shear in the mantle is believed to generate the anisotropic signature (Vinnik et al., 1992; Bostock and Cassidy, 1995; Russo et al., 1996).

Stations across Saudi Arabia

Aside from the additional complexity in the Gulf of Aqaba area, most of the splitting parameter observations across Saudi Arabia are very consistent. Yet, a straightforward explanation for these observations is difficult to apply. The observed north-south φ is not oriented perpendicular to the Red Sea Rift and therefore does not support a passive rifting model. Also, the orientation of φ is at least 30˚ different from the reported absolute plate motion direction (Figure 2). It is possible that the anisotropic signature obtained could be the result of fossilized anisotropy in the lithosphere, where φ is aligned parallel to the northerly strike of accreted terranes and sutures dating back to the Proterozoic assembly of the Arabian platform (Stoeser and Camp, 1985; Stern, 1994). Other cratons have been shown to display φ aligned parallel to Precambrian geology, and similar observations have been made in other rift environments as well (Gashawbeza et al., 2004; Silver, 1996; Walker et al., 2004). Using common percentages of anisotropy (4-5%; Mainprice and Silver, 1993), the lithosphere would need to be about 140 km thick to obtain the observed δt. However, xenolith temperature and seismic tomography studies indicate that the lithosphere thins to about 75 km near the Red Sea Rift (Almond, 1986; Camp and Roobol, 1992; Benoit et al., 2003) and receiver function analysis suggests that the lithospheric thickness is variable across the Arabian Shield (Tkalcic et al., 2005). Therefore, while fossilized anisotropy may contribute to the observed splitting parameters, it is unlikely the dominant cause.

Therefore, we feel that the observed splitting parameters are the result of a complex interaction of mantle flow in the asthenosphere. Shear caused by the absolute plate motion, which is directed approximately 40° east of north at about 22 mm/yr (Figure 3; DeMets et al., 1994; Reilinger et al., 1997), may affect the alignment of mantle minerals. However, it has also been suggested that flow radiating from the mantle plume beneath Afar is channelized towards the Red Sea Rift (Ebinger and Sleep, 1998), which is oriented approximately 30° west of north. Assuming that the strain caused by the plume flow is comparable to that of the plate motion, we can combine these two flow orientations, similar to the vector approach of Silver and Holt (2002). This gives an overall resultant that is oriented with a north-south alignment (Figure 3).

Mantle flow parallel to extension along the rift, such as in the passive rifting model, would also display a similar orientation to the plate motion. However, since the north-south orientation is also observed far from the rift axis, we favor the absolute plate motion as the contributing vector. Several other lines of evidence also help support our conclusions. Seismic tomography models have shown that the upper mantle beneath the western portion of the

Arabian Shield is anomalously slow, with velocities increasing towards the continental interior (Debayle et al., 2001; Benoit et al., 2003). These observations are attributed to thermal differences beneath Saudi Arabia and indicate much hotter mantle beneath the Red Sea than beneath the interior of the shield, which is consistent with plume flow directed beneath the rift. Surface wave and receiver function analysis shows that there is a change from vertical flow in southwest Saudi Arabia to horizontal flow further north, also consistent with the presence of channelized flow from the mantle plume (Tkalcic et al., 2005). Daradich et al. (2003) demonstrated that the higher elevations along the Red Sea Rift and the overall tilt of the Arabian plate result from viscous stresses associated with large-scale mantle flow from the Afar plume. In addition, Schilling et al. (1992) found isotopic evidence for mantle mixing between depleted asthenosphere and plume flow in Saudi Arabia, supporting the idea that an interaction of flow is occurring at depth. This combination of both plate and density driven flow may explain the observed anisotropic signature and is consistent with an active rifting model.

CONCLUSIONS

Teleseismic data recorded by the broadband instruments from three different seismic arrays have been used to examine shear-wave splitting along the eastern edge of the Red Sea and across Saudi Arabia. Stations in the Gulf of Aqaba display fast orientations that are aligned parallel to the Dead Sea Transform Fault. However, aside from this group, our observations across Saudi Arabia show a consistent pattern of north-south oriented fast directions with delay times averaging about 1.4 s. While fossilized anisotropy related to the Proterozoic assembly of the Arabian Shield may contribute to our observations, we feel that the anisotropic signature is best explained by a combination of plate and density driven flow in the asthenosphere. Combining the northeast oriented flow associated with absolute plate motion with the northwest oriented flow associated with the mantle plume beneath Afar generates a north-south oriented resultant that matches our splitting observations.

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REFERENCES CITED

Al-Amri, M., and Al-Amri, A., 1999, Configuration of the Seismographic Networks in Saudi Arabia: Seismological Research Letters, v. 70, p. 322-331.

Almond, D., 1986, Geological evolution of the Afro-Arabian dome: Tectonophysics, v. 131, p. 301-332.

Benoit, M.H., Nyblade, A., VanDecar, J., and Gurrola, H., 2003, Upper mantle P wave velocity structure and transition zone thickness beneath the Arabian Shield: Geophysical Research Letters, v. 30, doi:10.1029/2002GL016436.

Bostock, M., and Cassidy, J., 1995, Variations in SKS splitting across western Canada: Geophysical Research Letters, v. 22, p. 5-8.

Camp, V., and Roobol, M., 1992, Upwelling Asthenosphere Beneath Western Arabia and Its Regional Implications: Journal of Geophysical Research, v. 97, p. 15,255-15,271.

Christensen, N., 1984, The magnitude, symmetry and origin of upper mantle anisotropy based on fabric analyses of ultramafic tectonites: Geophysical Journal of the Royal Astronomical Society, v. 76, p. 89-111.

Daradich, A., Mitrovica, J., Pysklywec, R., Willett, S., and Forte, A., 2003, Mantle flow, dynamic topography, and rift-flank uplift of Arabia: Geology, v. 31, p. 901-904.

Debayle, E., Lévêque, J., and Cara, M., 2001, Seismic evidence for a deeply rooted low-velocity anomaly in the upper mantle beneath the northeastern Afro/Arabian continent: Earth and Planetary Science Letters, v. 193, p. 423-436.

DeMets, C., Gordon, R., Argus, D., and Stein, S., 1994, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions: Geophysical Research Letters, v. 21, p. 2,191-2,194.

Ebinger, C., and Sleep, N., 1998, Cenozoic magmatism throughout east Africa resulting from impact of a single plume: Nature, v. 395, p. 788-791.

Gao, S., Davis, P., Liu, H., Slack, P., Rigor, A., Zorin, Y., Mordvinova, V., Kozhevnikov, V., and Logatchev, N., 1997, SKS splitting beneath continental rift zones: Journal of Geophysical Research, v. 102, p. 22,781-22,797.

Gashawbeza, E., Klemperer, S., Nyblade, A., Walker, K., and Keranen, K., 2004, Shear-wave splitting in Ethiopia: Precambrian mantle anisotropy locally modified by Neogene rifting: Geophysical Research Letters, v. 31, doi:10.1029/2004GL020471.

Levin, V., and Park, J., 2000, Shear zones in the Proterozoic lithosphere of the Arabian Shield and the nature of the Hales discontinuity: Tectonophysics, v. 323, p. 131-148.

Levin, V., Henza, A., Park, J., and Rodgers, A., 2006, Texture of mantle lithosphere along the Dead Sea Rift: recently imposed or inherited?: Physics of the Earth and Planetary Interiors, in press.

Mainprice, D., and Silver, P., 1993, Interpretation of SKS-waves using samples from the subcontinental lithosphere: Physics of the Earth and Planetary Interiors, v. 78, p. 257-280.

Reilinger, R., McClusky, S., Oral, M., King, R., Toksoz, M., Barka, A., Kinik, I., Lenk, O., and Sanli, I., 1997, Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone: Journal of Geophysical Research, v. 102, p. 9,983-10,000.

Rodgers, A., Harris, D., Ruppert, S., Lewis, J., O'Boyle, J., Pasyanos, M., Abdallah, A., Al-Yazjeen, T., and Al-Gazo, A., 2003, A Broadband Seismic Deployment in Jordan: Seismological Research Letters, v. 74, p. 374-381.

Russo, R., Silver, P., Franke, M., Ambeh, W., and James, D., 1996, Shear-wave splitting in northeast Venezuela, Trinidad, and the eastern Caribbean: Physics of the Earth and Planetary Interiors, v. 95, p. 251-275.

Schilling, J., Kingsley, R., Hanan, B., and McCully, B., 1992, Nd-Sr-Pb isotopic variations along the Gulf of Aden: evidence for Afar mantle plume – continental lithosphere interaction: Journal of Geophysical Research, v. 97, p. 10,927-10,966.

Schmid, C., van der Lee, S., and Giardini, D., 2004, Delay times and shear wave splitting in the Mediterranean region: Geophysical Journal International, v. 159, p. 275-290.

Silver, P., and Chan, W., 1991, Shear Wave Splitting and Subcontinental Mantle Deformation: Journal of Geophysical Research, v. 96, p. 16,429-16,454.

Silver, P., 1996, Seismic anisotropy beneath the continents: Probing the depths of geology: Annual Reviews in Earth and Planetary Sciences, v. 24, p. 385-432.

Silver, P., and Holt, W., 2002, The Mantle Flow Field Beneath Western North America: Science, v. 295, p. 1,054-1,057.

Stern, R., 1994, Arc assembly and continental collision in the neoproterozoic east African orogen: Implications for the consolidation of Gondwanaland: Annual Reviews in Earth Planetary Sciences, v. 22, p. 319-351.

Stoeser, D., and Camp, V., 1985, Pan-African microplate accretion of the Arabian Shield: Geological Society of America Bulletin, v. 96, p. 817-826.

Taylor, J., 1982, An introduction to error analysis: the study of uncertainties in physical measurements, University Science Books, Mill Valley, California.

Tkalcic, H., Pasyanos, M., Rodgers, A., Gök, R., Walter, W., Al-Amri, A., and Al-Enezi, A., 2005, Lithospheric structure of the Arabian Peninsula from Joint Inversion of Teleseismic Receiver Functions and Surface Waves: EOS Transactions AGU, 86(52), Fall Meeting Supplemental, T13A-0449.

Vernon, F., and Berger, J., 1998, Broadband seismic characterization of the Arabian Shield: Final Scientific Technical Report, Department of Energy Contract No. F 19628-95-K-0015, p. 36.

Vinnik, L., Makeyeva, L., Milev, A., and Usenko, A., 1992, Global patterns of azimuthal anisotropy and deformations in the continental mantle: Geophysical Journal International, v. 111, p. 433-447.

Voggenreiter, W., Hötzl, H., and Jado, A., 1988, Red Sea related history of extension and magmatism in the Jizan area (Southwest Saudi Arabia): indication for simple-shear during Red Sea rifting: Geologische Rundschau, v. 77, p. 257-274.

Walker, K., Nyblade, A., Klemperer, S., Bokelmann, G., and Owens, T., 2004, On the relationship between extension and anisotropy: Constraints from shear wave splitting across the East African Plateau: Journal of Geophysical Research, v. 109, doi:10.1029/2003JB002866.

Wernicke, B., 1985, Uniform-sense normal simple-shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108-125.

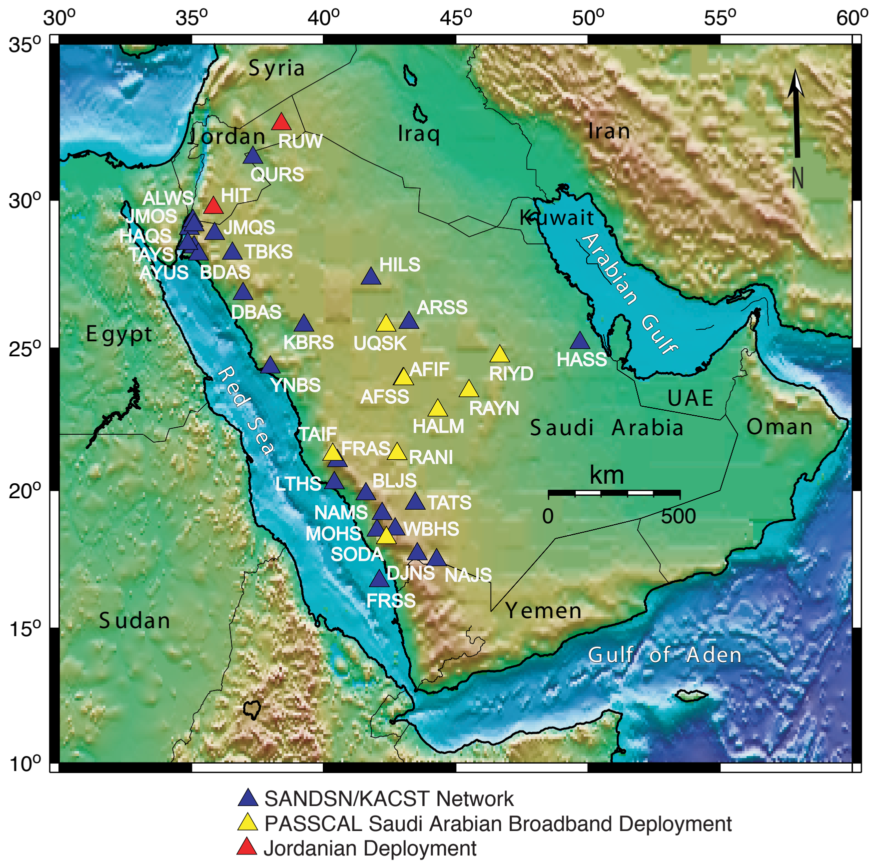
Wolfe, C., Vernon, F., and Al-Amri, A., 1999, Shear-wave splitting across western Saudi Arabia: The pattern of upper mantle anisotropy at a Proterozoic shield: Geophysical Research Letters, v. 26, p. 779-782.

FIGURE CAPTIONS

Figure 1. Station map showing the different arrays used in this study. The blue triangles are the broadband stations of the Saudi Arabian National Digital Seismic Network (SANDSN), the yellow triangles are the PASSCAL Saudi Arabian Broadband Array, and the red triangles are the two stations in Jordan. The corresponding names for each station are listed.

Figure 2. Map showing average splitting parameters. The bold, center lines at each station are oriented in the station's average φ and the length of the line is scaled to the average δt. The dashed "fans" show one standard deviation of the fast angle. The inset provides a closer view of the Gulf of Aqaba stations, whose respective names are also listed. The stations are the same as in Figure 1. The absolute plate motion direction is shown by the black arrow (DeMets et al., 1994; Reilinger et al., 1997).

Figure 3. Vector examination of plate motion (red arrow) coupled with channelized plume flow (blue arrow) beneath Saudi Arabia, similar to the approach of Silver and Holt (2002). If we estimate that the absolute plate motion is oriented 40º clockwise (CW) from North at a rate of about 22 mm/yr and that the channelized plume flow is oriented approximately 30º counter-clockwise (CCW) from North, then the rate of plume flow needed to obtain a north-south resultant (black dashed arrow) is about 27 mm/yr. Combining plate driven flow with density driven flow may explain the north-south oriented φ observed.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Jordanian Deployment

Figure 1

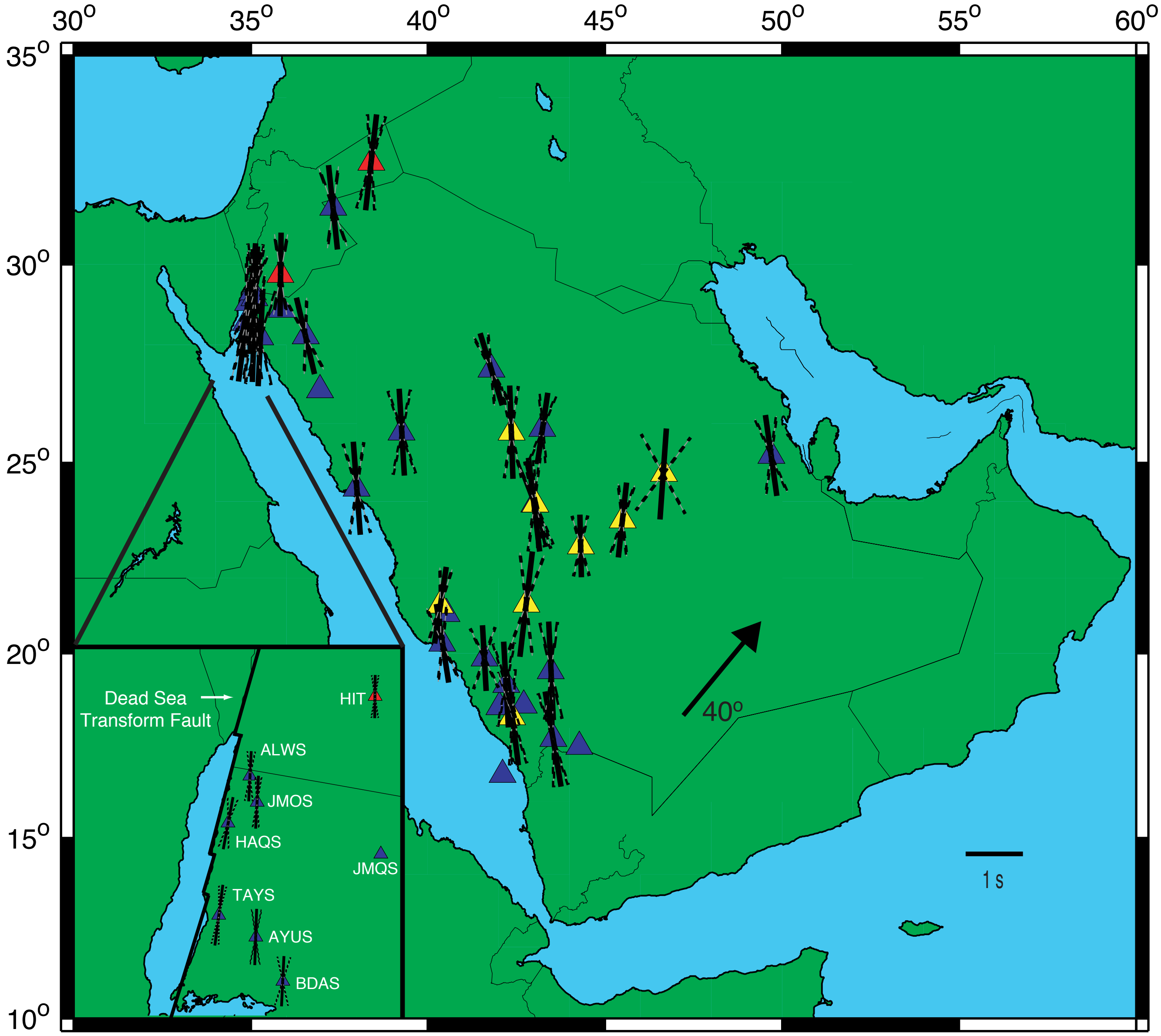

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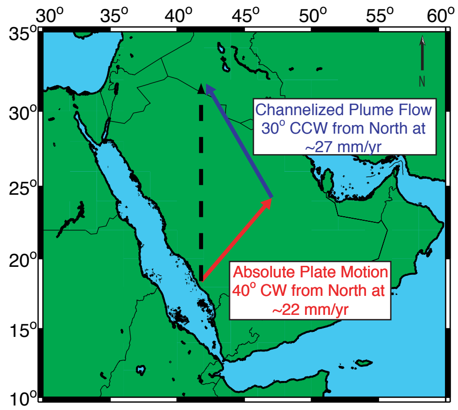
Figure 2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Channelized Plume Flow
30° CCW from North at
~27 mm/yr
Absolute Plate Motion
40° CW from North at
~22 mm/yr

Figure 3